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REMOTE SENSING FOR AGRICULTURAL WATER MANAGEMENT AND CROP YIELD PREDICTION

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ABSTRACT

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Research we have conducted over the past several years relative to agricultural application of remote sensing is reviewed. In addition, new data are presented from recent experiments reported here for the first time.

The subjects treated are soil moisture, evaporation, irrigation scheduling, and crop yield estimation. The analyses indicate that we have the technology at hand to successfully integrate remote sensing techniques into agricultural operations designed to enhance production via intelligent water management.

Avenues for additional fruitful research are indicated.

INTRODUCTION

If earth's atmosphere has had a lesson to teach mankind over the past few years, it has certainly been to demonstrate the wisdom of sound water conservation and management practices. From widespread droughts both within and without the United States, the ultimate dependence of both men and nations upon an adequate agricultural water supply has been amply illustrated again and again.

Long cognizant of this uncontrovertible fact, the agricultural research community has continued to update its approaches to water conservation and management with each new advance in technology. The current phase of this continuing modernization process could probably well be described as the dawning of the age of remote sensing in agriculture. As the National Aeronautics and Space Administration (NASA) has probed ever deeper into space, the USDA's former Agricultural Research Service, now Agricultural Research, Science and Education Administration, has focused its efforts on ways to use the fruits of space research to enhance the efficient production and distribution of food here on earth. In this paper we describe recent developments in some of the remote sensing aspects of this work that we have concentrated on at the U.S. Water Conservation Laboratory.

SOIL MOISTURE

Three years ago we reported on prospects for the detection of soil moisture by remote surveillance (Idso et al., 1975a). At that time the best results we had to offer dealt only with smooth, bare soils, and only with a thin surface layer of a few centimeters' thickness. Since that time we have gone on to consider water contents throughout the entire root zones of cropped fields, obtaining many indications that such determinations may soon be operationally feasible.

The approach we had used on bare soils that appeared to have a good potential to work on crops was to measure their emission of thermal radiation. Based upon the fact that water evaporation from plant leaves tends to cool them, and the fact that the source of this evaporated water is the active root zone of the crop, we postulated that root zone soil water content could be inferred from plant canopy temperature. Measurement of the canopy temperature by infrared thermometry would then give us a means to make this determination remotely. Similar suggestions and preliminary evidence for such a relation had also been presented by Tanner (1963), Wiegand and Namken (1966), and Ehrler (1973).

The first test of our hypothesis was made with data for a cotton crop grown at Phoenix, Ariz., in 1964, and two sorghum crops grown there in 1965 and 1966. The relationship we obtained is given by the solid lines of Fig.1a. Water contents for this relationship had been determined by integration of soil moisture profiles obtained by a neutron scattering technique (Van Bavel and Stirk, 1967) and plant temperatures by fine-wire thermocouples inserted into upper-canopy sunlit leaves. Air temperatures for these and all other leaf-air temperature differentials were obtained with shielded thermocouples about a meter above the crop.

The dashed lines of Fig.1a enclose a set of data points obtained on cotton 10 years later at the same location. In this instance the plant temperature data were obtained with an infrared thermometer having a 20 degree field-of-view, and held so as to view individual sunlit leaves. Figs.1b and 1c contain lines enclosing similar data sets for wheat and alfalfa, respectively. For both of these latter data sets, however, infrared thermometers viewed aggregations of plant leaves to give *canopy* temperatures.

In comparing parts a, b, and c of Fig.1, it is evident that although cotton, wheat, and alfalfa all display similar types of canopy temperature trends with changing soil water content, each crop exhibits a unique individual relationship. The two most different of these relationships are those for wheat and alfalfa. Wheat temperatures range from a lower limit of −4.5 to an upper bound of +6.0° C; while alfalfa temperatures stretch from extremes of −15 to +15° C.

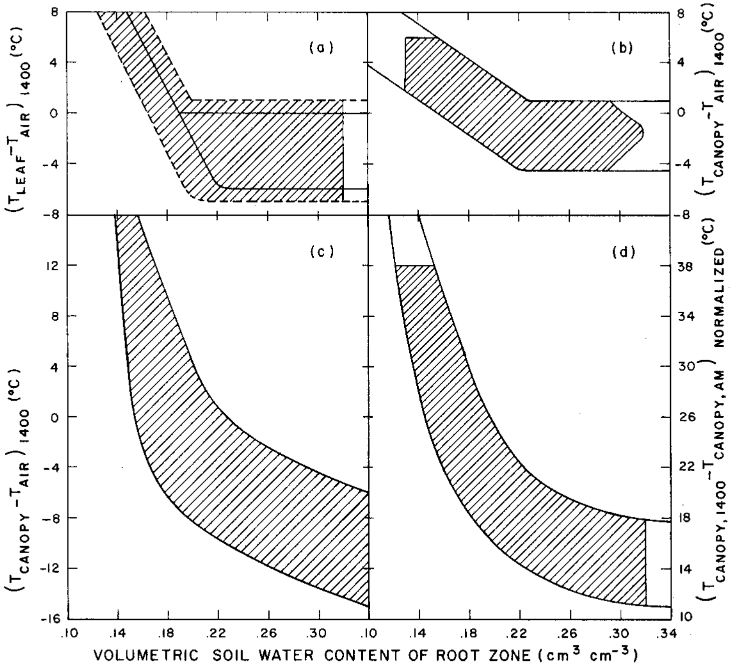

Fig.1. (a) The midafternoon (14.00 h) leaf-air temperature differential of individual sunlit cotton and sorghum leaves vs. the volumetric soil water content of the crop's root zone. The solid lines (Idso and Ehrler, 1976) are for leaf temperatures obtained by thermocouple, and the dashed lines for leaf temperatures obtained by infrared thermometer. (b) A similar relation for wheat utilizing infrared thermometer-derived *canopy* temperatures. (c) A similar relation for alfalfa utilizing infrared thermometer-derived canopy temperatures. (d) The midafternoon-presunrise canopy temperature differential of wheat and alfalfa normalized to remove effects of climatic variability as described in the text vs. the volumetric water content of the crops' root zones.

However, if midafternoon-presunrise canopy temperature differentials are utilized, rather than midafternoon canopy-air temperature differentials, and if these differentials are normalized for day-to-day weather variability as described by Idso et al. (1976), the results of Fig.1d indicate that these two most different crops can have their root zone water contents specified by a single common relationship. This latter approach is quite attractive from a remote sensing standpoint; for it uses only diurnal ranges of both canopy and air temperatures, and therefore does not require great absolute accuracy in the determinations of either of them.

EVAPORATION

We next focused our attention on the process of water loss by evaporation. Departing radically from all past approaches to the problem that had tended to minimize empiricism in favor of a complete analytical parameterization of the process, we were able to develop a very simple equation for *potential* evaporation from bare soil, the stage when water is available in sufficient supply in the soil to meet the atmospheric demand for evaporation. It was (Idso et al., 1975b):

$$E = 1.72 \times 10^{-2}\ [S_N + 1.56\,(R_A - R_G) + 156] \tag{1}$$

where E is the 24-hour evaporation rate in mm day^{-1}, 1.72×10^{-2} is a conversion factor for changing from energy evaporation units of cal cm^{-2} to mm of water evaporated, S_N is the net solar radiation absorbed by the surface during the day, 1.56 and 156 are empirical coefficients, and R_A and R_G are 24-h totals of incoming thermal radiation from the atmosphere and outgoing thermal radiation from the surface, respectively. R_A is calculated by means of the Idso—Jackson equation (Idso and Jackson, 1969), based solely on screen-level air temperature; while R_G is calculated by means of the Stefan—Boltzman equation, based solely on surface temperature. The averages of the daily maximum and minimum values of the air and surface temperatures are used as inputs for these latter two determinations.

Since eq. (1) was developed from data acquired on only one soil at one location (Phoenix, Ariz.), there naturally arose a question as to its generality (Kalma et al., 1977; McKeon and Rose, 1977), Thus, we conducted additional

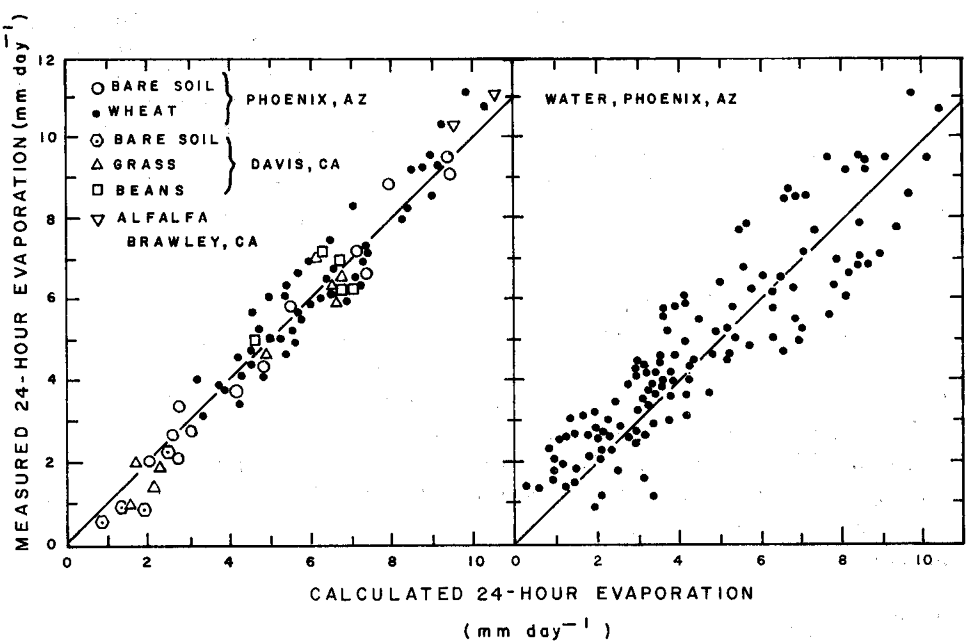

Fig. 2. Lysimetrically measured evaporation from several different surfaces vs. calculated potential evaporation by eq. (1). Results for water are shown separately, due to the reduced sensitivity of the lysimeter used to acquire the water evaporation data that introduced considerably more scatter into that data set. (After Idso et al., 1977b.)

evaporation experiments on wheat and open water at Phoenix; bare soil, grass, and field beans at Davis, Calif.; and alfalfa at Brawley, Calif., where lysimeters were available to directly measure evaporation rates. The results (Idso et al., 1977b) showed that eq. (1), even without any modification of the two empirical coefficients, adequately described the 24-h potential evaporation rates from all of these different surfaces, as depicted in Fig.2.

One reason for the success of eq. (1) in all of these different applications is that it uses as an input parameter the surface temperature, which is a great integrator of many other important environmental factors. Thus, although windspeed and vapor pressure varied over wide ranges among our several different investigations, and directly influenced evaporation rates, eq. (1) adequately predicted these evaporation rates without explicit consideration of these parameters; for it is the resultant evaporation rate itself that to a large degree determines the surface temperature. This procedure of using a sort of after-the-fact measurement to determine its cause reflects a unique aspect of the remote sensing point of view that led us to develop eq. (1) and which could be a springboard from which other important developments may come. It is like evaluating the clues at the scene of a crime to determine what has happened, whereas the prior more conventional approach generally tries to project what will happen from an analysis of factors affecting the criminal's state of mind leading to the commission of the act.

Just recently we have made an attempt to broach the subject of non-potential evaporation calculation within a remote sensing context (Idso et al., 1978a). We found that for the classical stage III of soil drying — defined as the regime where the rate of water loss from the soil is governed by adsorptive forces acting over molecular distances at liquid—solid interfaces, and identifiable by reflected solar radiation measurements (Idso et al., 1974) — that the evaporation is given by eq. (1) multiplied by the factor 3/8. For transitional stage II evaporation ($E2$), we have additionally determined that

$$E2 = \beta PE + (1-\beta)\, E3 \qquad (2)$$

where PE is the potential evaporation rate given by eq. (1), $E3$ is the stage III evaporation rate, and β is a "partitioning factor" determined by Jackson et al. (1976) to be expressable as

$$\beta = \frac{\alpha_d - \alpha}{\alpha_d - \alpha_w} \qquad (3)$$

where α_d is the dry soil reflectance or albedo, α_w is the wet soil albedo, and α is the albedo of the soil in the range of intermediate conditions. Since the albedo determination introduces no new measurements not already required to calculate PE or $E3$, all of these approaches to evaporation calculation require no new data beyond what is required for utilization of eq. (1). Since they have only been tested on one soil, however, the expressions for $E2$ and $E3$ must still be considered preliminary, and subject to possible future modification.

We have also made a preliminary investigation into the calculation of non-potential evaporation from crops where plants are sufficiently stressed to reduce evaporation below the potential rate. In a study of wheat we determined that vegetative non-potential evaporation (VNP) was adequately determined by eq. (1) multiplied by the expression $[0.68-0.1(T_C-T_A)]$. Again, the use of canopy temperature (T_C) and air temperature (T_A) introduces no new parameters not already appearing in eq. (1). However, more experimentation remains to be done before the confidence we attach to eq. (1) may be associated with the expression for VNP. Nevertheless, as with soil moisture, there is much evidence that portends eventual operational success for the remote sensing of all phases of evaporation from both bare soils and cropped fields.

CROP YIELDS

There are a variety of different methods that have been used over the years to calculate crop yields. The current Large Area Crop Inventory Experiment (LACIE) symbolizes a merger of remote sensing and conventional approaches to the subject. Utilizing satellite measurements of reflected solar radiation in several different wavebands to identify crop types and determine their spatial extent, LACIE incorporates standard rainfall and air temperature data into historical regression models to estimate crop yields (Hammond, 1975). One of our approaches has been to develop an independent technique for crop yield assessment that relies on only the remotely sensed portion of the LACIE data base; while a second approach has been to develop a technique that utilizes canopy-air temperature differentials.

The minimum albedo approach

This approach relies on the measurement of reflected solar radiation only. Data obtained by Idso et al. (1977c) at Phoenix, Ariz., and Hatfield et al. (1978) at Davis, Calif., indicate that the albedo of a wheat field follows a characteristic course over the growing season. In Phoenix, where the dry soil albedo was very high, the wheat field albedo gradually decreased from the time of plant emergence; while in Davis, where the dry soil albedo was very low, the wheat field albedo gradually increased, due to the effects of the increasing leaf area index. In both cases, however, once the leaf area index had reached a maximum and the soil was no longer visible, wheat field albedo continually decreased from the time of heading to the time of grain ripening, when the browning of the crop drastically increased albedo once again.

Idso et al. (1977c) originally postulated that the lower the albedo dropped prior to its final rise, the higher would be the yield of the crop. We also postulated that since the underlying soil was effectively removed from view by the proliferation of the crop, and since the minimum albedo measurement was, again, an after-the-fact type of measurement — that is, it was a measure of what was actually "there" — that this relation would be essentially universal in applicability for the specific crop with which we worked. Our more recent test of these hypotheses (Idso et al., 1978c) appears to substantiate them. For three different planting rates in two different locations in two different years with a variety of irrigation-induced soil moisture regimes, the grain yield of Produra wheat bore a unique relationship to the minimum albedo reached just prior to grain ripening (Fig.3).

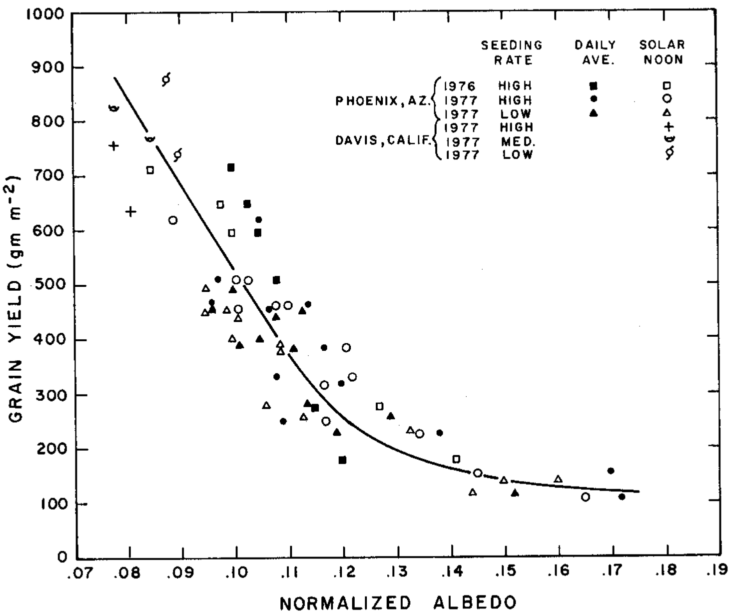

Fig. 3. Grain yield of Produra wheat vs. the minimum value of crop albedo reached just prior to grain ripening. Effects of variable solar zenith angle over the season at the two locations have been removed to normalize the albedo values. (After Idso et al., 1978c.)

The stress degree day approach

This approach is based primarily upon canopy temperature measurements. Since water stress results in elevated plant temperatures, as discussed earlier, and since such water stress implies a photosynthetic stress (Idso, 1968), we postulated about 2 years ago that there was a direct link between plant temperatures and crop yields (Idso et al., 1977a). In particular, we devised a "stress degree day" (SDD) concept, much like the old growing degree day (GDD) concept, whereby crop yield (Y) was hypothesized to be inversely and linearly related to the total SDD's accumulated over some critical period in the crop's life cycle. This notion can be expressed mathematically as

$$Y = \gamma - \delta \sum_{i=h}^{e} \mathrm{SDD}_i \tag{4}$$

where SDD_i is the midafternoon (about 2 p.m.) value of $(T_C - T_A)$ on day i, and h and e represent the days on which the summation is to begin and end. For grain crops we took the critical period for SDD summation to extend from the appearance of *h*eads and awns to the *e*nd of plant growth; while for a forage crop such as alfalfa, we found that dry matter production per unit area was a linear function of SDD's summed over the entire period of vegetative growth (Reginato et al., 1978).

Recently we have generalized the SDD concept by combining it with the GDD concept in a way that enables us to predict both final yield and the time of cessation of crop growth (Idso et al., 1978b). Whereas our earlier procedure embodied by eq. (4) was somewhat site-specific, our new approach also appears to be independent of climate. Thus, its utility is greatly increased in two different ways.

The combined GDD, SDD model is portrayed in Fig.4, with the growing degree day parameter defined in the usual way as

$$\mathrm{GDD} = \frac{T\mathrm{max} + T\mathrm{min}}{2} - T_{\mathrm{b}} \tag{5}$$

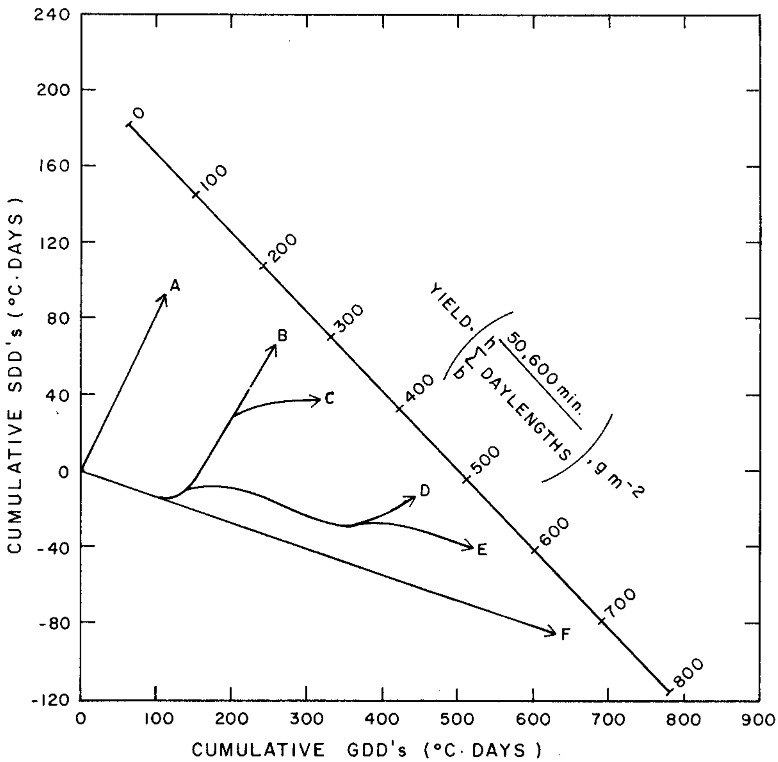

Fig.4. Grain yield of Produra wheat as a function of both stress degree days and growing degree days accumulated from the time of appearance of heads and awns. Lines A, B, C, D, E, F represent typical "routes" by which six differently irrigated plots approached final yield at Phoenix, Ariz., in 1976. (After Idso et al., 1978b.)

where Tmax and Tmin are daily maximum and minimum air temperatures and T_b is a base temperature below which physiological activity is assumed inhibited, taken to be 5.5° C in this example. Starting at time h (GDD = 0, SDD = 0), accumulations of both GDD's and SDD's are plotted so as to depict a "route" by which the crop "travels" from heading to the end of plant growth. When the yield line is intersected by one of these "routes", the value read from the graph is multiplied by the number of daylight minutes between the time of plant emergence and heading that the mean daily air temperature was above T_b, and then divided by 50 600 min. The result is the predicted yield for the crop. Depending upon the past history of the crop and the probability with which the future weather may be predicted, it is evident that yield predictions can be made in this way soon after heading. As the yield line is more closely approached with the passing of time, the final prediction can be refined to an increasingly more accurate figure. Results based upon the actual intersection values have shown no tendency for systematic error.

IRRIGATION SCHEDULING

In addition to estimating crop yields and harvest times, the combined GDD, SDD concept can be utilized to schedule irrigations. In Fig.4, for instance, it is evident from time h (GDD = 0, SDD = 0) that plot A is heading for a low yield, and that it should have been irrigated prior to heading, as were all of the plots B through F. Best yields are obtained when irrigations are given so as to accumulate negative totals of SDD's in this format. Thus, whenever there is a significant upswing in the crop's "route", such as near the GDD values 115 and 350 for plot E, irrigations should be given. Of course, they can be given at later times, as in the case of plot C, and some good can come from such water; however, there has been an irreparable loss of potential yield that can never be recouped by that time. Conversely, water can be supplied to the crop before it is called for, as with plot F, which was irrigated about every 10 days during this period; but the extra gain in yield may not be worth the price of the extra water.

As an additional check upon this approach to irrigation scheduling, in our first full season's work with wheat we carried out an extensive program of plant water stress measurement (Ehrler et al., 1978). From concurrent measurements of plant canopy temperature acquired by infrared thermometry and plant water potential (ψ_{plant}) acquired by the Scholander pressure bomb technique, we were able to document the relationship shown in Fig.5. The ψ_{plant} value of −19 bars for $T_C - T_A = 0$ corresponds to a volumetric soil water content of 0.20 (obtained from concurrent applications of a neutron scattering technique to evaluate the root zone soil moisture, θ_v). The difference between this value of θ_v and the value of 0.28 for the soil at "field capacity" represents a 62% depletion of the available water in the root zone, using $\theta_v = 0.15$ as the wilting point. On the same and similar soils, this percentage depletion has been used for the proper time of irrigation to obtain maximum production con-

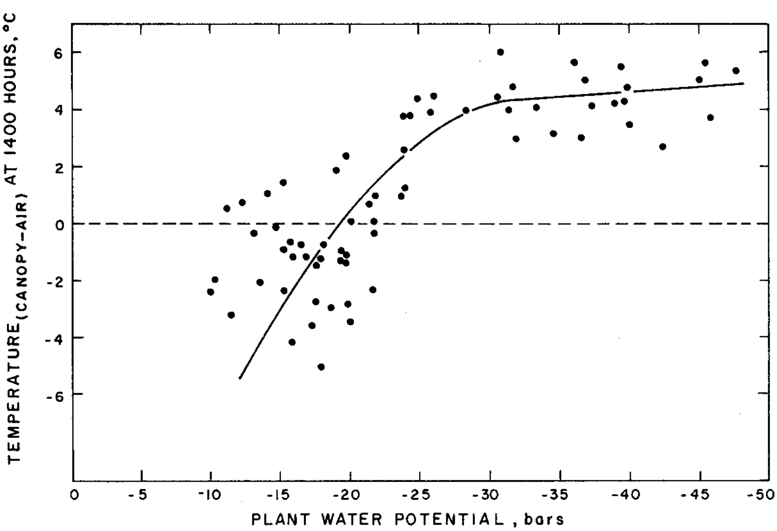

Fig. 5. The midafternoon canopy-air temperature differential for Produra wheat vs. the whole plant water potential. (After Ehrler et al., 1978.)

sistent with efficient water use for a wide variety of crops (Erie et al., 1965, 1973).

THE FUTURE

Where do we go from here? There are two major areas of research that need continued intensive nourishment to eventually bring about the promised revolution in farm management that is held out by the dawning of the age of remote sensing in agriculture. One deals with further development and testing of ideas of the type we have outlined here, and the other deals with the development and testing of instrumentation and operations systems to implement these ideas.

In the realm of further idea development and testing, we are continuing our work in all four areas of soil moisture estimation, evaporation calculation, crop yield prediction, and irrigation scheduling. In particular, we are expanding our cooperation with other locations, as well as looking at different crop types and considering other possible input parameters.

Concurrently, the nuts-and-bolts aspects of the work are proceeding from the aircraft and satellite level. Continuing our policy of instrumentation and systems verification along with the basic idea development, as described by Reginato et al. (1976, 1977) and Millard et al. (1978), a 2500-acre barley field near Dunnigan, Calif., was recently systematically surveyed from the air twice weekly for surface temperature by NASA personnel. The successful April launch of NASA's experimental Heat Capacity Mapping Mission satellite means that we will also be acquiring several pixels of surface temperature and reflectance data for the Dunnigan site on close to the same schedule, both prior to sunrise and about an hour and a half past solar noon.

Extrapolating the results of these efforts into the future — as well as those of many other investigators — the promises of remote sensing for a better national and international system of water management and crop yield assessment appear bright indeed. The not too distant future should see many of them fulfilled.

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